UVPROM Dosimetry Aboard The MPTB Satellite: Method Optimization And Implementation

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Abstract

A commercial Ultraviolet erasable Programmable Read Only Memory (UVPROM) is used to demonstrate the technique for both ground and space dosimetry applications. An equivalent amount of UV to reproduce the same amount of erasure is used to calibrate dose. The method of readout does not require the evidence of exposure to be destroyed. The method requires power only during readout. Results from an experiment using this technique aboard the Microelectronics and Photonics Test Bed (MPTB) satellite are discussed. Application of extreme value theory is used to analyze whether early failures in the device are statistically feasible or more likely due to large, rare energy depositions. A new dosimeter approach using a change injection method that will eliminate the need for UV as a metric is also presented as well new experiments for the DUTs aboard MPTB.

I. INTRODUCTION

An EPROM is a non-volatile memory that stores information in the form of charge on a floating gate. The floating gate's charge sets the digital state of the cell. Ionizing radiation generates electron-hole pairs in the oxides of MOS devices [1], and some of the holes can be expected to reach the negatively charged floating gate and recombine with electrons stored on the gate. The result is the gradual neutralization of the charge stored on the floating gate [2-3]. Zeros are stored in memory elements of UVPROMs by loading the gate to capacity with negative charge. Given sufficient exposure to ionizing radiation, the floating gates lose enough charge that they can no longer maintain their transistors in the programmed state, and there is a 0 to 1 soft error.

If one such error is generated within a program that is essential to spacecraft systems, it can have catastrophic consequences. This paper describes a procedure for estimating the amount of charge removed from the floating gates of a UVPROM in order to monitor exposure. It also presents the results from two AM27C64 UVPROMs after 2700 highly elliptical orbits. Extreme value theory is used to analyze whether initial failures in the DUTs are statistically improbable. Finally, a new experiment is proposed measure microdose level single events and provide real time mapping of the belt.

II. THEORY

The use of a UVPROM as a dosimeter follows from the fact the UV erases the programming of the device. The transistor has two gates; a control gate at bias Vpp and a floating gate which is insulated from the rest of the circuit, as shown in Figure 1. The two states of the transistor in a normal read operation are determined by whether the floating gate is charged with electrons or left uncharged in programming. Depending on the charge on the floating gate, the channel will or will not conduct when the read voltage (5V) is applied to the control gate. If the floating gate is uncharged, a positive bias on the control gate results in electrons being attracted to the channel, allowing current to flow as long as the floating gate is uncharged. This is called the "conducting" state of the FET. Likewise, the "non-conducting" state occurs when there is sufficient charge on the floating gate to drive electrons away from the channel. Exposure to radiation reduces the amount of charge on the floating gate until the transistor changes from the non-conducting to the conducting state. In normal operation, the only information regarding the status of the charge on the floating gate occurs when the logic state of the transistor switches states.

Electrons on the floating gate need 3.2 eV to be removed by direct ionization [1-3]. Silicon requires an average of 3.6 eV to generate an electron-hole pair [1]. Radiation with energy less than the SiO_2 band gap width will generate holes in the surrounding silicon, some fraction of which will then be injected into the oxide [1-3]. The exact method of hole-pair generation in the oxide, then, depends on the radiation energy, the electric fields involved, the type of oxide, etc. [4].

In SiO_2, the mobility of the negative carrier, the electron, is 10^6 - 10^{11} times larger than the mobility of the hole [1]. The charge generated in the dielectric causes a fast diffusion current of electrons that flows to positive regions. The holes flow much more slowly to the negative poles. When the FAMOS transistor has all leads floating, the floating gate presents the only negatively charged area. The holes approach the floating gate and induce tunneling thereby reducing the charge on the floating gate. An energetic charged particle generates electron-hole pairs according to its LET, and the amount of charge removed from the gate depends on the LET and the proximity of the trajectory to the gate.

While the thermal effects of this system have not been studied in detail, enough data has been gathered to surmise that the effect of temperature is not a dominant issue. Previous studies indicate that the detector is fairly stable for the normal operating temperature ranges [4].

On the MPTB satellite with its transfer orbit similar to the CRRES satellite, the primary radiation exposures are to electrons due predominately to the exposure in the earths radiation belts. Occasional hits with heavy ions generate large amounts of localized ionization, but these occasional hits contribute only a small amount to the total dose.

This paper will also examine the effect of dose to single cells in two ways. First, a statistical method of analysis called Extreme Value Theory will be used to examine the early failures of sections of UVPROM cells [6]. For N number of units in a distribution, which is also the number of cells in the system, this expands to:

$$F_{EV}(t) = 1 - \left(1 - F(t)\right)^N \qquad (1)$$

where F(t) is the cumulative distribution which describe the system. For the target theory which has shown to describe the erasure distribution of the UVRPOM very well [5]:

$$F_{EV}(t) = 1 - \left(1 - \left(1 - \exp\left(-\frac{t}{C}\right)\right)^D\right)^N \qquad (2)$$

and

$$f_{EV}(t) = \frac{ND}{C}\left(1 - \left(1 - \exp\left(-\frac{t}{C}\right)\right)^D\right)^{N-1}\left(1 - \exp\left(-\frac{t}{C}\right)\right)^{D-1}\exp\left(-\frac{t}{C}\right) \qquad (3)$$

which is the extreme value distribution for the first flip. Figure 2 shows the extreme value response of a ground test of similar devices. Equation 3 describe the distribution of first failures of the target theory systems, i.e. given a large number of identical target theory systems the distribution of first events will follow Eq. 3.

Small volume effects are also studied by investigating the use of short duration programming pulses on the device as the metric of measuring dose. Sufficiently small programming pulses should be able incrementally load the floating gate with electrons. Pulse length can range from nanoseconds to milliseconds and the both Vpp and Vcc can be varied to minimize noise or increase response. All other aspects of this study will parallel UVPROM dosimeter investigations to discern the change in accuracy and precision of the method of using change in erasure time with UV as the metric of dose measurement. The need for increased autonomy and duty cycle of floating gate dosimeters necessarily required an alternative to UV being used as a metric for measuring dose. The reproduction of highly precise UV is very difficult and the device also exhibits sensitivity to the manner in which UV is used to erase or calibrate the device. Also, the need for dosimeters that are complete electrical and compact necessarily requires that UV be eliminated as a metric.

III. Procedure And Calibration

The exact dosimetry method of the MPTB experiment is described in detail in reference 4 and will only be summarized here. The memory array of an AM27C64 UVPROM consists of 65,536 FAMOS transistors. The standard method for erasure is to expose the device to UV radiation. Ultraviolet light with energy of 4.8 eV (254nm) was used in this study to calibrate the system. Photons of energy less than 8 eV have been shown not to damage the oxide or to generate interface states while generating holes in the oxide [1-4].

When the charge is sufficiently reduced on a gate, its state will switch from the off (gate loaded or 0) state to the on (gate neutralized or 1) state. All gates were loaded in programming by putting all memory locations in the non-conducting or 0 state.

The total number of erase bits is plotted versus the duration of UV exposure in Figure 3. The values at low voltages on the Vpp pin (< 9 V) forms the curve on the right while the curve on the left represents the values obtained at high voltages (> 9.4 V). These curves exhibit the S-shape familiar in studies of probabilistic phenomena.

As seen from the curves in Figure 3, the removal of charge on the floating gate can only be observed as a bit flip over a very narrow range of exposure levels. It is important that a dosimeter be sensitive over its entire exposure range. This can be accomplished by keeping some memory elements in the array at peak sensitivity over the entire range of expected exposure levels. Pre-exposing some portions of the array to different amounts of UV before using the array as a dosimeter does this. Since the die of the device is too small to expose UV exclusively on a fraction of the cells, another method was devised. A cycle of exposing a programmed chip and reprogramming decreasingly smaller sections of address space allows each of the partitions of memory space to receive a different net exposure. This creates the desired steps of erasure and guarantees that the DUT is at peak sensitivity regardless of the exposure.

An algorithm for automating the dose measurement follows from the figures above. Following exposure to ionizing radiation and the partitions having been read, checking which partitions are in the sensitive region and comparing them with a pre-irradiation run can obtain a coarse estimate of the dose received. Those partitions in the sensitive region are checked to determine whether the ratio of the logic state at low voltages to high voltages is a value found during calibration.

Incremental Charge Injection Method

As described above, to eliminate UV as the metric or radiation dose, the amount of programming time at various values of Vpp is used. To use this device as a passive dosimeter, the device is programmed and exposed to radiation. Each cell will require programming to replace the charge lost from the floating gate due to radiation. The amount of programming should correspond to dose. In practice, the device programmed with short duration pulses and a characteristic curve is developed. The period of programming time or the number of programming pulses for recovery of the programmed state can be measured from this curve. A FAMOS cell programs very quickly due to the high voltage

(~12V) on the control gate. For the DUT used in this study, programming time at manufacturer specified is on the order of nanoseconds. Supply programming pulses as short as these were considered prohibitive due to noise in the lines and difficulty reproducing exact pulse on this time scale. To allow for longer pulses, the voltage on the control gate was lowered to allow for microsecond resolution of the programmed pulses required to program the device, or each cell. Figure 4 shows a family of characteristic curves from conditioning a DUT for exposure. Each curve indicates the number of programmed bits as a function of the programming time for microsecond pulses. Each curve had a different Vpp voltage applied during readout. A curve is chosen as the readout voltage and then programmed and irradiated. The resulting change in the time to program until completely programmed will correspond to dose.

Use of the UVPROM as a micro-dosimeter is conceptually the same as the dosimeter. The difference lies with addressing and programming a single bit and measuring the number of pulses that bit required to change from reporting unprogrammed to programmed, in the micro-dose case. In this manner, each cell can function as a micro-dosimeter and report local energy deposition from rare, energetic events.

Since each cell can be electrically isolated, the number of programming pulses, or programming time, can be measured and recorded. Also, each cell can be measured for micro-dose without affecting any other cell, something that cannot be done using UV. Ion LET is expected to have a large effect of the response as extrapolated from previous studies [4-7]. Oxide effects are also expected to affect response [1].

IV. RESULTS

A. UV Metric Dosimeter Results

Figure 5 shows the response of the dosimeter in UV metric mode to three different types of radiation. The value plotted on the ordinate of each graph is the equivalent UV exposure was divided by the total UV exposure required to flip all bits in the memory array and is called the “fraction erasure.” The top graph shows the results 200 MeV protons at Indiana University. The relationship in this case is not linear but follows a power law relationship. The exponent of the power law is 0.8. The deviation from a linear relationship is probably due to proton effects on the oxide that are not generated by UV exposure, principally the increased lattice interface states and bulk trapped charge. The net effect of the two trapped charge types artificially suppresses the effects of floating gate charge on the conduction state of the channel [1-6]. This experiment was repeated at different angles of incidence and different energies but no dependence was observed.

The middle graph of Figure 5 shows the effect of electrons on the device. The exponent of the power law in this case is 0.7. The bottom graph of Figure 5 shows the results for 210 MeV chlorine ions exposure done at the Tandem Van de Graaf facility at BNL. The data is again best fit by a power-law relationship. The exponent in this case is 0.5. Again, the deviation from a linear relationship may be due to oxide effect suppressing the number of holes reaching the floating gate electrons. There is a much larger spread in data here that may be due to the extreme value of the LET and the damage done to single cells. These ions had a LET of 11.40 MeV cm^2 mg^{-1}.

B. MPTB Results

Two AMD27C64 UVPROMs were placed on the card in slot 6 on panel C of the MPTB satellite experiment as part of an array of EEPROM and UVPROM devices for which the exposure to ionizing radiation is independently measured. They are partially shadowed by reinforcement straps that were added during installation of the experiment onto the satellite. The circuit reads all the memory elements of all devices on the card, and it reads the elements on the two UVPROMs while varying the Vpp voltage. The data is downloaded to earth. The results matched with calibrations to get fraction erasure as a function of orbit.

The data was sent down as the logic states for every partition on two devices, and estimates of the fraction erasure were carried out. The UVPROMs have had identical results. Figure 6 shows the data obtained from the first 2777 orbits. The first data was received for orbit 41. The orbits were highly elliptical transfer orbits and orbit-to-orbit fluctuations are expected even in a quiet environment.

The satellite entered a major ecliptic season after orbit 160. About 20 orbits later, the logic states of the partitions exhibited sudden changes that appear as large jumps in the estimates of the fraction erasure as is clearly seen in Figure 7. This may be due to charging effects on the circuit elements and/or the circuit board. Such an effect can be replicated in the laboratory if static charge is allowed to build up on the circuit elements and eventually discharged. Discharging restores the circuit and data. Similar effects have been studied on CRRES and other satellites. [4]

Since the effects of circuit charging are recognizable, they can be removed from the data by a simple algorithm that removes sudden jumps up or down. The result of the application of this algorithm is shown in Figure 6. Since most of the dose received on MPTB is from electrons in the quiescent environment, it is possible, using the results shown in Figure 5, to convert fraction exposure to equivalent electron dose in Rads(Si). The resulting plot of absorbed dose versus orbit number is shown in Figure 8. Figure 8 also shows the conversion to dose if an average of proton and electron dose is used and also if a linear response is assumed.

Each board in the MPTB experiment is equipped with a PMOS radfet dosimeter. Figure 8 shows the three UVPROM dose estimates along with what is reported by MPTB’s dosimeters. There are two major discrepancies. The first is a general factor difference between the two methods. The dose reported by the UVPROM is consistently lower than that of the on-board radfets. The second discrepancy is the non-constant factor of this offset. To see these discrepancies clearer, the response of the MPTB dosimeters is plotted against the estimated electron dose, Figure 9, and the raw response of the DUTs, Figure 10. There are two definite regions to both graphs. There is a linear region below 35 krad(Si) and a linear region above 35 krad(Si). The transition point between these two regions corresponds to orbit 750, or about 20 krad(Si) as reported by the UVPROM method. Ground testing of the UVPROM and similar radfets to the ones aboard the MPTB satellite are currently underway in dose environments similar to space.

After approximately 1000 orbits, partitions that had been almost completely programmed, i.e. were launched reporting zero erasures, began to show first errors. These partitions are almost completely erased by the MPTB radiation environment and therefore show any large, rare energetic radiation events as large early erasures. These partitions can be analyzed with extreme value theory. Figure 11 shows the number of erased bit as a function of dose determined by the UVPROM. A target theory fit was generated for the device and the resulting extreme value distribution was also generated. As can be seen from the figure, the first event occurs between one and two standard deviations of the maximum of the extreme value distribution. This is not surprising since the using the dose predicted by other sections of the device to analyze the device is begging the fundamental question. This analysis is important though to show the analyzed section is behaving normally. Figure 12 shows the number of failures using dose reported from MPTB. Here, the first erasure occurs before the maximum, about one standard deviation, of the extreme value distribution.

V. New Design Implementations

A. Charge Injection Metric Dosimeter Results

Since UV light removes electrons from the floating gate, being able to measure the DUT response to UV is an important benchmark. Figure 13 shows the response of DUT used to measure UV. A completely erased curve as well a several levels of exposure to UV are included. These are typical curves, and the curves are typical of DUT noise. Figure 14 shows the amount of programming time required to return the device to a programmed state. The relation is linear, as expected. Figure 13 and Figure 14 illustrate the method of using the device as a total dose dosimeter.

Measurement of gamma from the JPL Cobalt-60 source at 50 krad(Si)/s is shown in Figure 15. Results from two DUTs are shown. The response is non-linear and has a power law response. The exponent of the power law is approximately 0.8. Gamma was expected to exhibit a similar response to measurements done in previous studies with this device. [5].

An important note concerning irradiation should be illustrated here. The response of the FAMOS cells to short pulse programming changes for an irradiated device. The voltage on the Vpp pin should be increased after irradiation. A Vpp of 9.2V to 9.5V is used for irradiated devices. This change in Vpp is due to charge building up in the channel oxide due to irradiation and has not been seen to anneal. The response of the dosimeter remains intact.

B. Charge Injection Metric Micro-dose results.

Micro-dose results are defined as the response of individual cells to radiation. To determine that these devices function as micro-dosimeters, selected bits must be capable of detecting and measuring irradiation on a small scale. To observe this, six identically prepared DUT were exposed to ions of various LET. As outlined above, 1000 bits were selected. The fluence was chosen to be 3.3e7 cm^2. This fluence was assumed to result in a hit to each floating gate on average. The irradiation was done at Texas A&M Cyclotron using the Krypton and Argon 25 MeV/u beams. LET was adjusted using degraders. The result of reading out the devices for number of flips is shown in Figure 16. The figure plots the cross section per bit for reporting erasure. The point at the 30 MeV-cm^2/mg value is uncharacteristically high and maybe due to a range effect of the higher LETs. The relation is monotonically increasing function and is linear if the 30 LET point is omitted. The noise in the graph is in part due to part-to-part variation. The spread in the data has been seen before [5].

Each bit that reports an erasure requires a certain amount of programming time to return it to the programmed state. Figure 17 shows the normalized mean programming time required to return the erased bits to the zero state. The normalization is the quotient of the average number of pulses required to program after irradiation to the mean amount need to prepare the same bits. The relation is not linear and is fitted to a logarithmic function. This agrees with previous results in the response of the device to differing LETs[4-7]. Oxide effects are assumed to play a role here [15].

This effect plays a very important role in the MPTB experiment because some of the partitions in the experiment are now fully erased. And the experiment provides the right amount of voltage for the slower incremental programming. Therefore, the spent partitions could be reprogrammed to become single particle detectors and microdosimeter. An algorithm could be uploaded to provide the necessary programming algorithms. And considering the prompt response of the charge injection method, the actual dose profile of the electron belts could be mapped in real time.

V. Conclusions

New dosimetry approaches using FAMOS FETs have been developed. Ionizing radiation neutralizes the charge on the floating gates that can be measured through the pins of a commercial UVPROM. Procedures and algorithms have been developed to provide an estimate of the absorbed dose. Exposures to electrons, protons, and heavy ions result in different power-law responses relative to UV. Reading the data does not destroy or alter the data, nor does it prevent continued measurement with the same device. The sensitivity of commercial UVPROMs to ionizing radiation is suitable for applications on spacecraft where the radiation environments are expected to be harsh. The radiation exposure can be monitored confidently with a resolution of about 10 Rad(Si) with the current system. Work is ongoing to increase the sensitivity in order to be useful for personnel monitoring as well as microdose and SEU studies. Techniques are also being developed to extend the range of these dosimeters for longer measurement cycles and extremely harsh environments.

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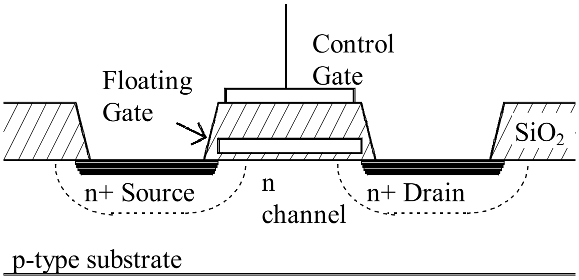

Figure 1: A FAMOS transistor. The floating gate stores charge so the device may power down and still retain data. Ionizing radiation removes charge from the floating gate.

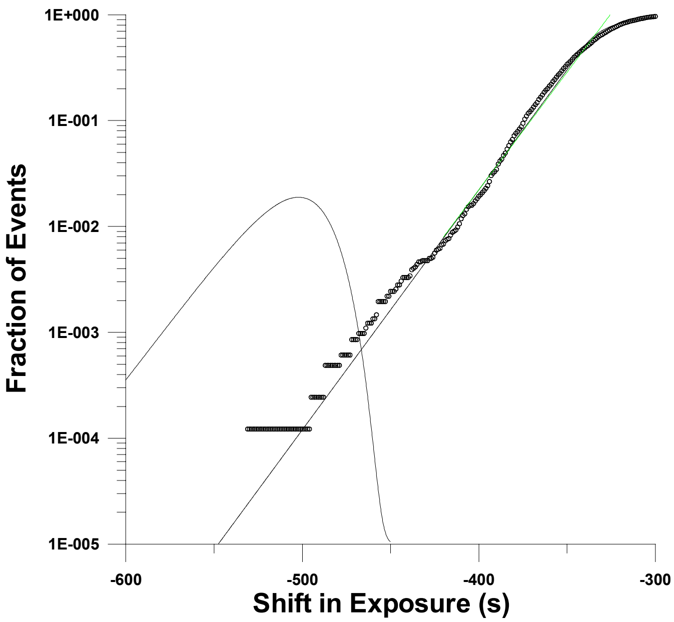

Figure 2: Demonstration of extreme value theory. The structure of the cumulative events is fit by a distribution. The extreme value theory is given by Eq. 3 and is the peaked curve on the left. It is the distribution of the first failures.

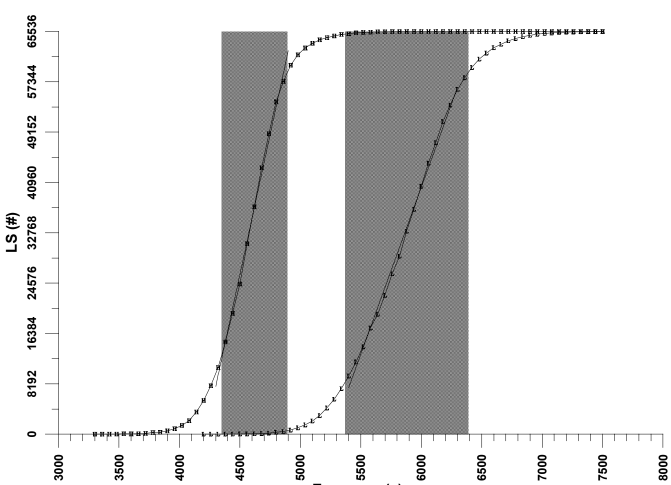

Figure 3: The number of erasures obtained with high Vpp (> 9.4 V), and the value obtained at low Vpp (< 9 V) plotted versus the duration of UV exposure.

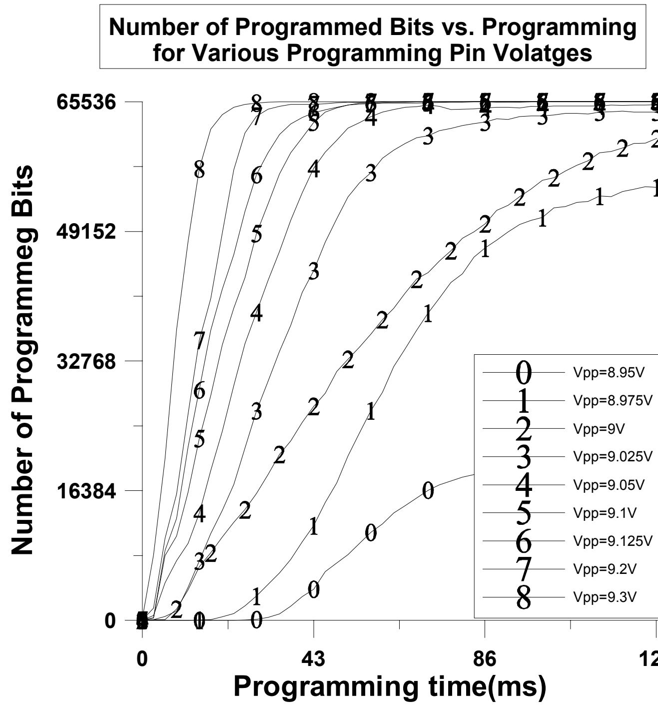

Figure 4: Charge injection response of the UVPROM.

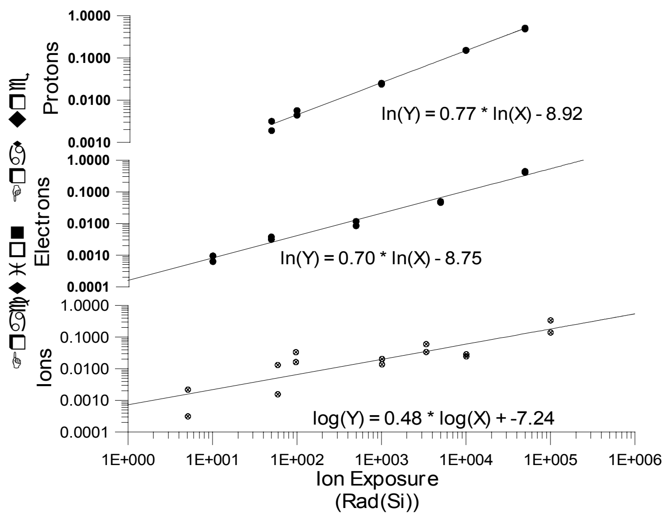

Figure 5: Response of the UVPROM to three types of radiations The top graph is Proton exposures to 200 MeV protons at the Indiana university Cyclotron facility. The middle graph is 6 MeV electrons done at the Greenville Memorial Hospital. The bottom graph is 210 MeV Chlorine ions done at the Tandem van de Graaf at Brookhaven National Laboratory.

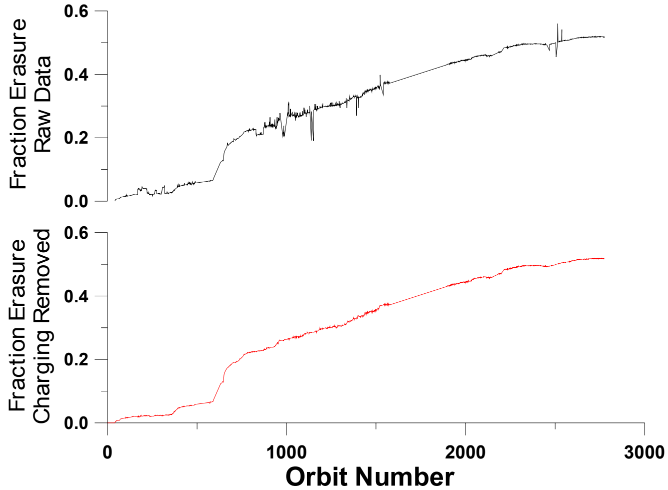

Figure 6: Fraction erasure for two UVPROMs flown as part of the MPTB experiment plotted versus orbit number. The smoothed curve is shown below the raw data curve

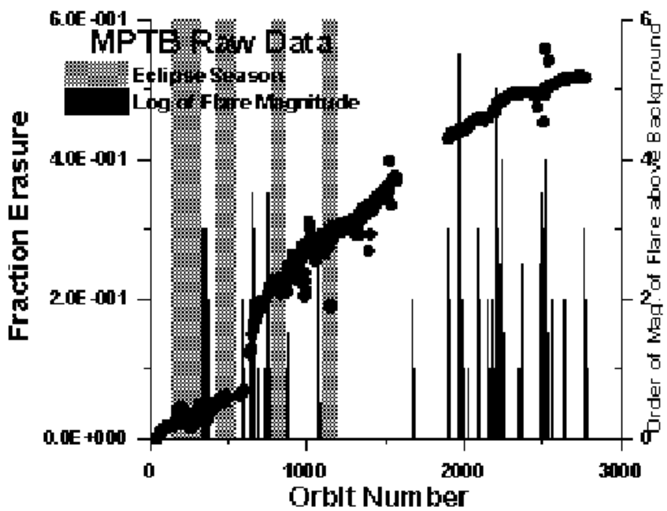

Figure 7: Raw data of fraction erasure shown superposed with flares (log axis on the right) and eclipse season. Charging occurs mostly during eclipse season.

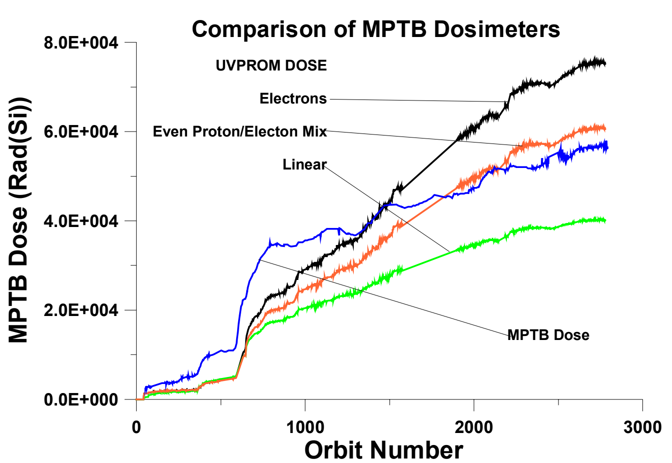

Figure 8: Dose measured by the UVPROM system compare the on-board dosimeters on MPTB.

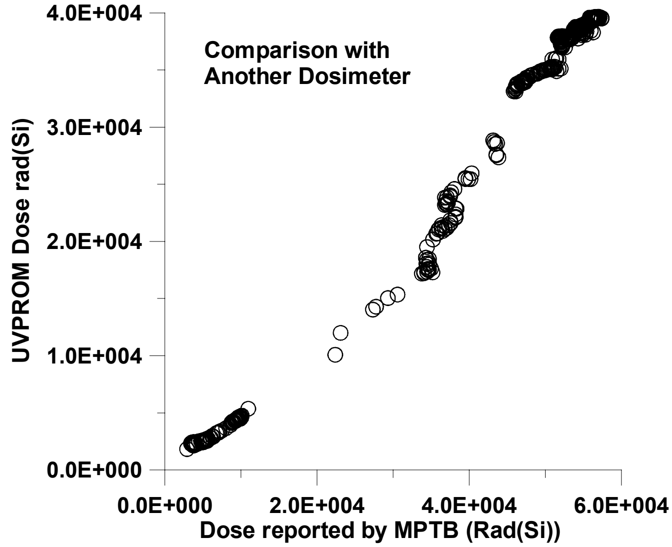

Figure 9: UVPROM dose compared to MPTB dose.

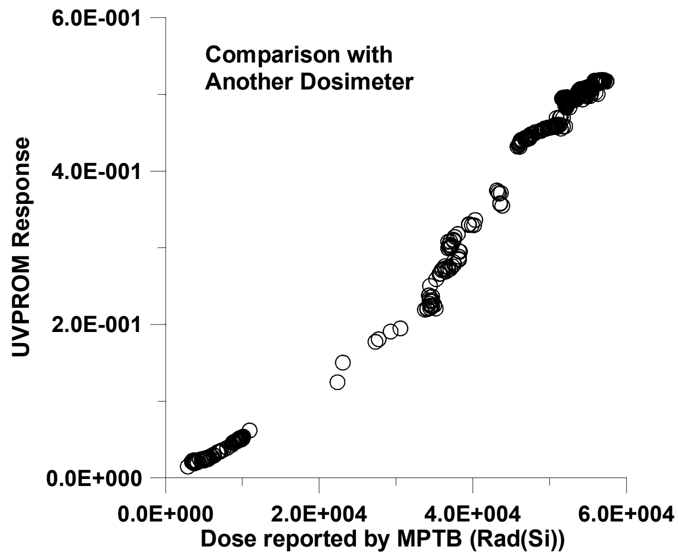

Figure 10: UVPROM response plotted versus MPTB dose response.

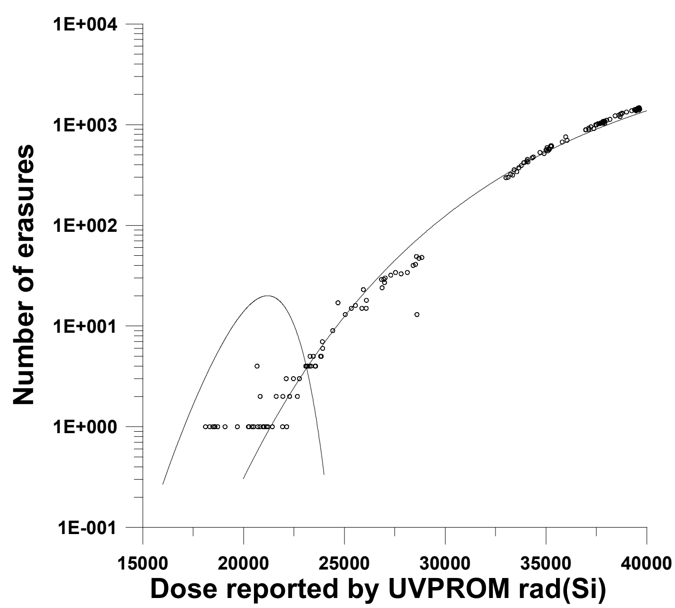

Figure 11: Dose of 6 MeV electrons required to produce the equivalent fraction erasure observed on MPTB versus orbit number.

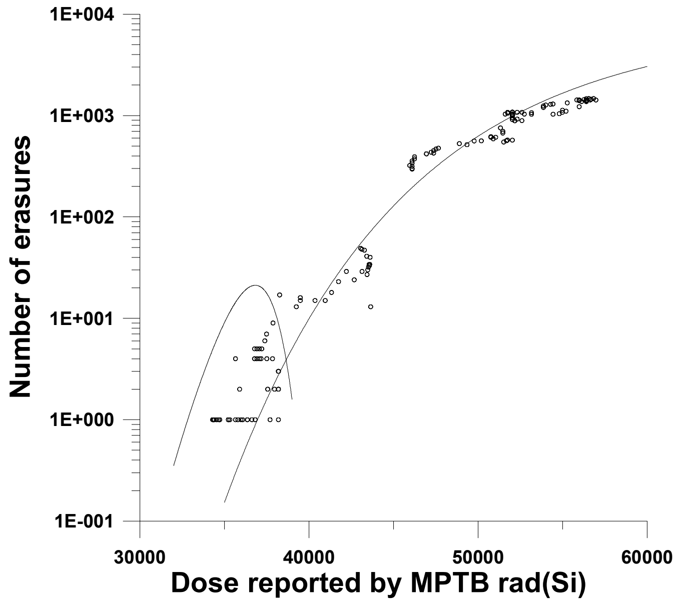

Figure 12: Dose of 6 MeV electrons required to produce the equivalent fraction erasure observed on MPTB versus orbit number.

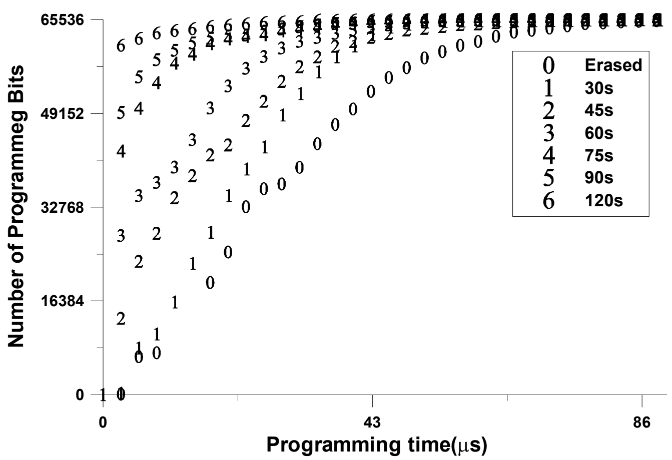

Figure 13. A total dose measurement run using UV as the radiation. This is a typical curve that shows the DUTs sensitivity to noise. Averaging compensates for the noise issues.

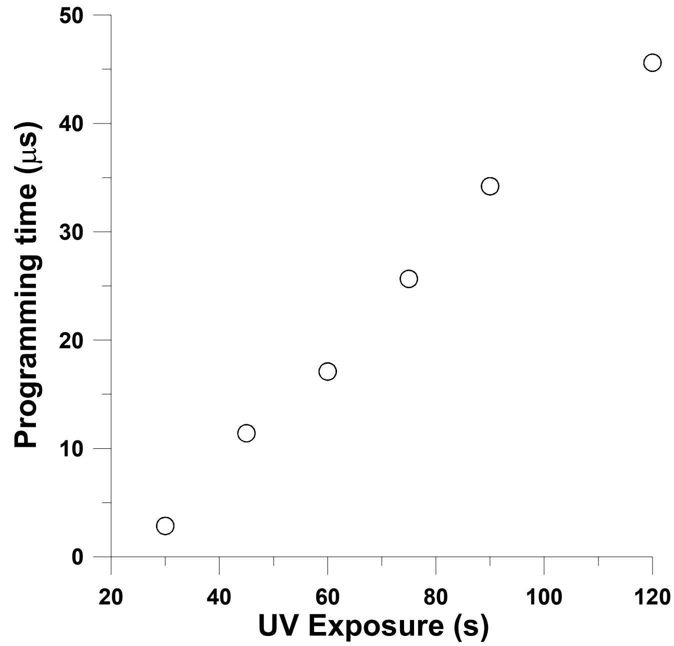

Figure 14. A total dose measurement run using UV as the radiation. This relationship was expected to be linear and is seen to be. Since the UV does not damage the device or limit endurance lifetime, this relationship reveals the upper bound of the system's precision.

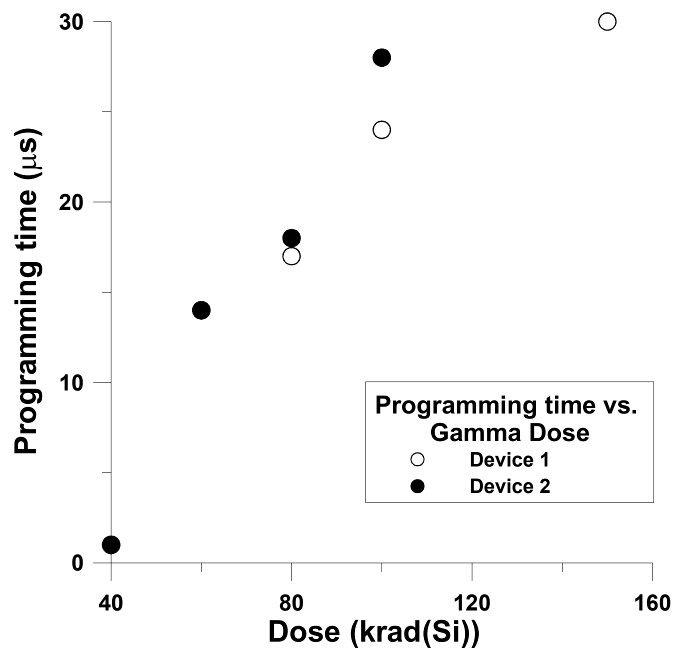

Figure 15: Total dose repsonse of two different devices of two different ion at BNL. The relationship is a power law and aggrees with earlier studies.

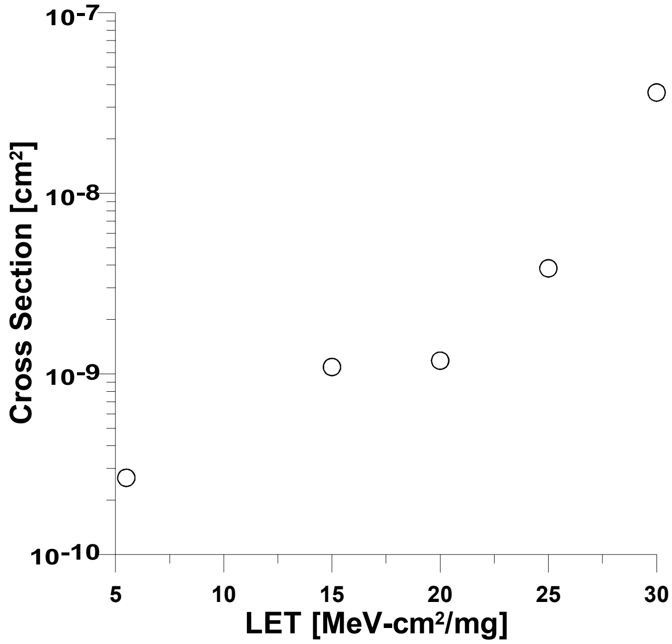

Figure 16. Bit cross section for various LETs. The ordinate values are the number of reported bit erasures divided by the number of selected bits, 1000 in this experiment, and fluence on the part, 3.3e7 cm^2, to hit each floating gate once on average.

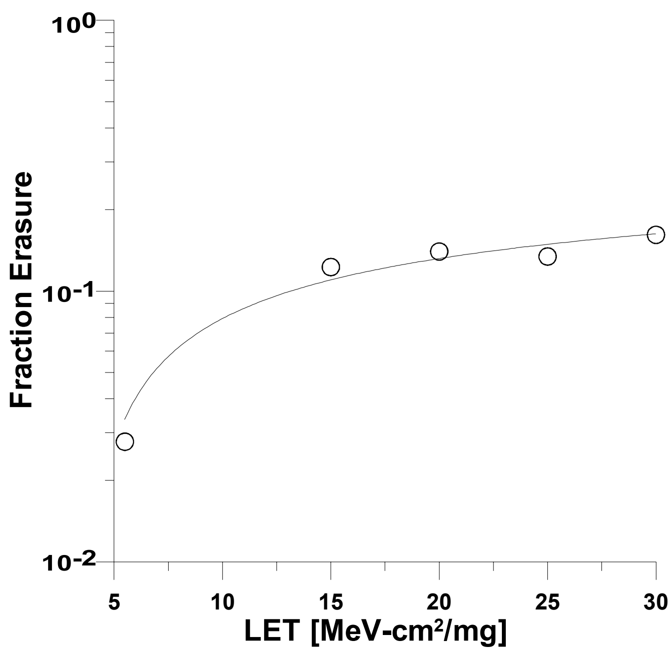

Figure 17. Normalized mean programming time for various LETs. Each cell that reported erasure requires a number of programming pulse to return it to the programmed state. The ordinate value to the average programming time require to return the bit to the programmed states divided by the number of programming pulse require to prepare the device.